

The $\bar{N}N$ quasi-bound states: J/ψ and atomic evidence¹

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Abstract.

The measurements of J/ψ decays into $\gamma p\bar{p}$ show a strong enhancement at $p\bar{p}$ threshold not seen in the decays into $\pi^0 p\bar{p}$. What is the nature of this enhancement? A natural interpretation can be performed in terms of a classical model of $N\bar{N}$ interactions based on G -parity transformation. The observed $p\bar{p}$ structure is the consequence of the strong attraction in the 1S_0 state related predominantly to π -meson exchanges. Similar attractions generate near threshold: a virtual (or quasi-bound) state in $^{11}S_0$ -, a quasi-bound state in $^{33}P_1$ - and a resonance in $^{13}P_0$ -waves. These P -wave structures find support in the \bar{p} -atomic data.

INTRODUCTION

An old question in the antiprotonic physics is the existence or non-existence of exotic $N - \bar{N}$ systems: quasi-bound, virtual, resonant, multiquark or baryonium states [1]. Such states, if located close to the threshold, would generate large scattering lengths for a given spin and isospin state. The scattering experiments offer the easiest check but a clear separation of quantum states is not easy. Complementary measurements of the X-ray transitions in \bar{p} atoms may select certain partial waves when the level fine structure is resolved. This resolution was achieved in the 1S states [2] and partly in the 2P states [3] of hydrogen. Another method to reach selected states are formation experiments. Along this way, the BES Collaboration [4] measured the decays

$$J/\psi \rightarrow \gamma p\bar{p} \quad (1)$$

and found an enhancement close to the $p\bar{p}$ threshold. A clear threshold suppression is seen in another decay channel $J/\psi \rightarrow \pi^0 p\bar{p}$. Conservation laws limit quantum numbers of the $p\bar{p}$ states allowed in those decays. The final state $p\bar{p}$ interactions reduce these further to one state per channel. While the \bar{p} -hydrogen determines scattering lengths (volumes), the J/ψ decays allow to extend this knowledge to energies above the threshold. To look below the $p\bar{p}$ threshold one needs heavier \bar{p} atoms.

Two studies are presented in this contribution:

¹ Invited talk (S. Wycech) to the International Conference on LOW ENERGY ANTIPROTON PHYSICS (LEAP05), May 16-22, 2005, Bonn-Jülich, Germany to appear in AIP series of conference proceedings.

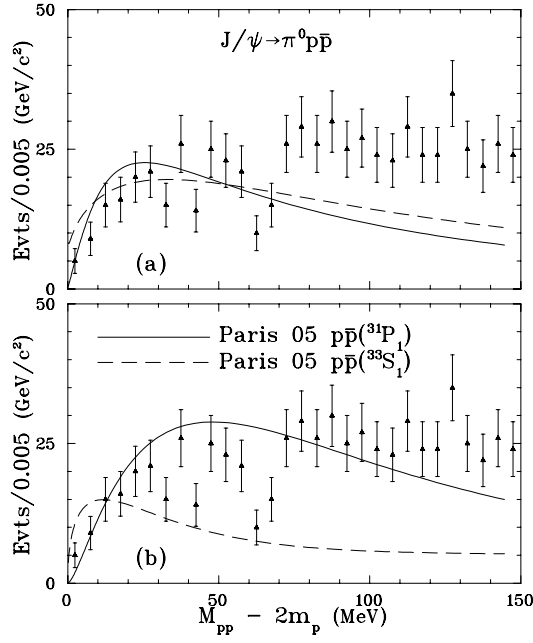


FIGURE 1. The $\pi^0 p \bar{p}$ decay channel. The experimental data has been extracted from Fig. 2(a) of Ref. [4]. The solid and dashed lines represent the results obtained with the $^{31}P_1$ - and $^{33}S_1$ -waves of the recent version [8] of the Paris potential, respectively. The previous version of the Paris potential [9] give similar results. (a) The final state factor $q |T_{ff}/q^L|^2$ (Watson approximation). The constant C_{if} is chosen to fit the low-energy part of the data. This approximation fails for $M_{p\bar{p}} - 2m_p > 40$ MeV ($q > 1$ fm $^{-1}$). (b) The rate $q |T_{if}|^2$ of Eq. (2). The constant A_{if}^0 and the formation range parameter $r_o = 0.55$ fm are chosen to obtain a good fit to the data. Here, the $^{31}P_1$ wave reproduces well the data. A 18 MeV wide state bound by 18 MeV is generated with the Paris model [8] in the $^{31}P_1$ wave, but it has little effect on the results.

- The J/ψ decay mode (1) is discussed and the threshold $p\bar{p}$ enhancement is attributed to a broad subthreshold state in the $^{11}S_0$ wave.
- The atomic level shifts are related to the \bar{p} -nucleus zero energy scattering parameters A_L . In light atoms the latter are extracted from the $\bar{p}d$ -, $\bar{p}^3\text{He}$ -, $\bar{p}^4\text{He}$ -data. Next, A_L are expressed in terms of the $\bar{p}p$ -, $\bar{p}n$ -subthreshold lengths $a(E)$ and volumes $b(E)$. Due to the differences in nuclear binding one can obtain, in this way, the energy dependence of $\text{Im } a(E)$, $\text{Im } b(E)$. This dependence indicates a P -wave quasi-bound state.

THE $\bar{P}P$ FINAL STATE INTERACTIONS IN J/ψ DECAYS

The J^{PC} conservation reduces allowed $p\bar{p}$ final states to several partial waves. These (denoted by $^{2I+1}2S+1L_J$) differ by isospin I , spin S , angular momentum L and total spin J . A different threshold behaviors of $p\bar{p}$ scattering amplitudes is expected in different states. Three partial waves are allowed in reaction (1). Two states 3P_0 and/or 1S_0 are preferred by the angular distribution of photons, but a transition to 3P_1 wave is also possible [4, 5]. Two waves $^{31}P_1$ and $^{33}S_1$ are possible in the $J/\psi \rightarrow \pi^0 p \bar{p}$ channel.

One expects the $p\bar{p}$ interactions to dominate the final state which becomes an effective

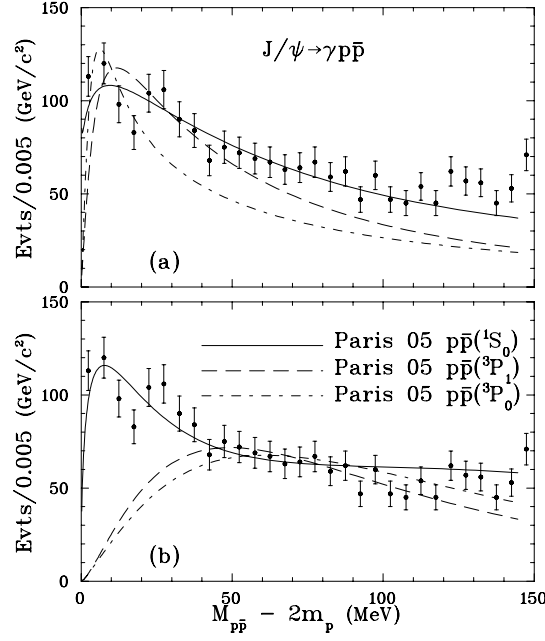


FIGURE 2. The $\gamma p \bar{p}$ decays. Data as in Fig. 1. The solid, dashed and dot-dashed lines represent the results obtained with the 1S_0 -, 3P_1 - and 3P_0 -waves of [8], respectively. (a) The final state factor $q |T_{ff}/q^L|^2$ (Watson approximation). At $q > 2 \text{ fm}^{-1}$ this approximation begins to fail. (b) The rate $q |T_{if}|^2$ of Eq. (2) with $r_o = 0.55 \text{ fm}$. The 1S_0 -wave of [8] offers the best fit to the data. It involves a quasi-bound state in the 1S_0 -wave located very close to threshold, of 53 MeV width and 5 MeV binding.

two body channel. The transition amplitude from an initial channel i to a two-body channel f may be presented as

$$T_{if} = \frac{A_{if}}{1 + iqA_{ff}} \quad (2)$$

where A_{if} is a transition length, A_{ff} is the scattering length in the channel f , and q is the momentum in this channel. The scattering amplitude in channel f is given by

$$T_{ff} = \frac{A_{ff}}{1 + iqA_{ff}}. \quad (3)$$

In the process of interest the formation amplitude A_{if} is unknown, but A_{ff} is calculable in $N\bar{N}$ interaction models constrained by other experiments. For slow $p\bar{p}$ pairs one expects $A_{if} \sim q^L$ and $A_{ff} \sim q^{2L}$. Thus the quantity $C_{if} \sim A_{if}q^L/A_{ff}$ may be weakly energy dependent, which is the essence of Watson-Migdal approximation $T_{if} \approx \text{const} \times q^{-L} T_{ff}$. It is frequently true in a small energy range where the denominator in Eq. (2) provides all the energy dependence. In the $p\bar{p}$ states such an approximation is correct for q up to about 0.5 fm^{-1} . It fails at higher momenta since A_{ff} is energy dependent as a result of π exchange forces. This has been pointed out in Ref. [6] on the basis of an one-boson exchange version of Bonn potential. A similar behavior is seen with the Paris model [5] although these two potentials differ strongly in the two-pion sector. On the other hand, A_{if} stems from a short range $c\bar{c}$ annihilation process.

TABLE 1. Level shifts in antiprotonic deuterium and He, [keV] for $1S$, [eV] for P states. Third column gives the extracted scattering lengths and volumes.

level	$\Delta E - i\Gamma/2$	$A(L)[fm^{2L+1}]$
D, $1S$	1.05(25)-i0.55(37) [2]	0.71(16)- i0.40(27)
D, S	scattering [14]	- i0.62(7)
D, $2P$	243(26) -i245(15) [2]	3.15(33) - i3.17(19)
^3He , $2P$	17(4) - i25(9) [15]	4.3(1.0) - i6.3(2.2)
^4He , $2P$	18(2) - i45(3) [15]	3.5(0.4) - i8.8(1.0)

The annihilation range is of the order of $1/m_c$ [7] and only a weak energy dependence is expected in A_{if} . We assume $A_{if} = A_{if}^0 q^L / (1 + (r_o q)^2)^{L+1}$ with a range parameter r_o well below 1 fm and a constant A_{if}^0 .

The results. The phenomenological A_{ff} are fairly well determined by the scattering data. Here, these are calculated in terms of the updated Paris $N\bar{N}$ potential model [8]. The model itself is fitted to 3400 $\bar{p}p, \bar{n}p$ scattering data used in the earlier version [9] and it involves the data from the $\bar{n}p$ scattering Ref. [10] and $\bar{p}p$ atoms. Figures 1 and 2 present the results. Both decays find a natural explanation in this fairly traditional model of $p\bar{p}$ interactions based on G -parity transformation, dispersion theoretical treatment of two-pion exchange and semi-phenomenological absorptive and short range potentials. Quasi-bound states close to the threshold are predicted in $p\bar{p}(^{13}P_1)$, $p\bar{p}(^{11}S_0)$ waves and a resonance in the $p\bar{p}(^{13}P_0)$ wave. The first two indicate a strong dependence on the model parameters. The third one, the resonant state, is well established [11, 12]. In order to see better the nature of this predictions one should look directly under the $p\bar{p}$ threshold. An analysis of the low-energy $\bar{p}d$ scattering or $\bar{p}d$ atoms allows that, at least in principle. Next section discusses chances to achieve that.

SUBTHRESHOLD AMPLITUDES EXTRACTED FROM \bar{P} ATOMS

Experiments which detect the X-rays emitted from hadronic atoms provide electromagnetic levels shifted and widened by nuclear interactions. For a given n -th state of angular momentum L these complex level shifts $\delta E_{nL} - i\Gamma_{nL}/2$ are closely related to the threshold scattering parameters A_L , [13],

$$\delta E_{nL} - i\Gamma_{nL}/2 = \epsilon_{nL}^o \frac{4}{n} \prod_{i=1}^L \left(\frac{1}{i^2} - \frac{1}{n^2} \right) \frac{A_L}{B^{2L+1}} (1 - \lambda A_L / B^{2L+1}). \quad (4)$$

Eq. (4) is an expansion in A_L/B^{2L+1} which is small in all accessible states (B is the Bohr radius). The contemporary precision of the experiment requires $1S$ state correction ($\lambda = 3.154$) to be included (few %), otherwise it is negligible. The numbers given in table 1 follow from Eq. (4) and correspond to an average over the unresolved fine structure.

In $\bar{p}d$ the scattering lengths and volumes may be calculated quite reliably by a summation of the multiple scattering series. For a full explanation of the method we refer to [16], it compares successfully with exact calculations. Here it is extended to the

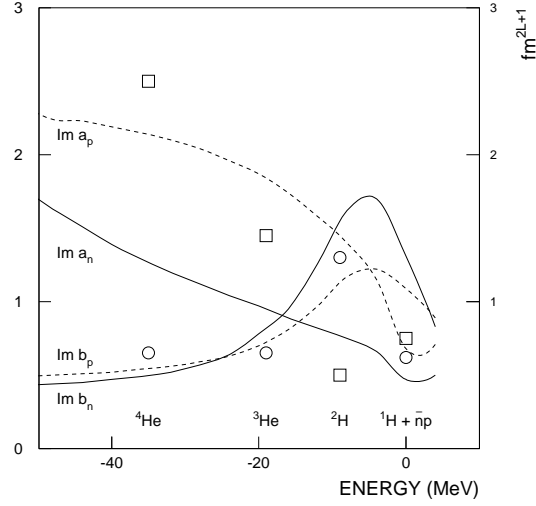


FIGURE 3. The absorptive parts of subthreshold amplitudes calculated with Paris model [8]: dotted lines - $\bar{p}p$, continuous lines - $\bar{p}n$. The lengths are denoted as a_p, a_n the volumes b_p, b_n . The $b_p/2 + b_n/2$ should be compared to the circles which give the average scattering volumes extracted from d , ${}^3\text{He}$ and ${}^4\text{He}$. In the same way the extracted scattering lengths given by the squares are to be compared to $(a_p + a_n)/2$. The data support the possible existence of $p\bar{p}({}^{33}P_1)$ quasi-bound state found in this model. In the S wave case, the statistically insignificant ${}^{11}S_0$ state is possible but not clearly seen.

$L = 2, 3$ states in \bar{p} He. At zero \bar{p} energies there are four basic $\bar{p}N$ amplitudes of interest

$$f_{\bar{p}N}(E) = a_N(E) + 3b_N(E)\mathbf{p} \cdot \mathbf{p}' \quad (5)$$

where N stands for the proton or neutron, \mathbf{p} and \mathbf{p}' are the initial and final $\bar{p}N$ CM momenta. In each case the lengths a and volumes b are averaged over spin states. In deuterium (and other light nuclei) these amplitudes appear to, a good approximation, via the energy averaged values

$$\bar{a}_N = \int a_N(-E_B - \frac{p^2}{2m_{rec}}) |\tilde{\phi}_d^L(p)|^2 d\vec{p}, \quad (6)$$

which reflect the nucleon binding E_B and the recoil of the spectator. The volumes are averaged in a similar way. For d , the extent of the involved energies is determined by the Bessel transforms of the wave function

$$\tilde{\phi}_d^L(p) = \int \psi(r) j_L(pr/2) r^2 dr \quad (7)$$

These energies cover some unphysical subthreshold region. The relevant distributions given by Eq. (6) peak around -12 and -7 MeV for $L = 0, 1$ states. For heavier nuclei and stronger nucleon bindings the energies of interest are shifted further away from the threshold. That gives the chance to study the energy dependence of $\bar{a}(E)$ and $\bar{b}(E)$.

The \bar{p} -nucleus scattering parameters may be expressed in terms of these averages $A_L(\bar{b}, \bar{a})$ by summation of the multiple scattering series. The data consists of $1S, 2P$ widths + shifts in Deuterium, $2P$ width + shifts and $3D$ widths in ${}^3\text{He}$, ${}^4\text{He}$. With four

basic energy dependent parameters a, b a unique resolution is not possible. A best fit result may be obtained for $\text{Im } a(E)$ and $\text{Im } b(E)$. In this case additional data from the \bar{p} stopped in d and He chambers [17, 18] allow to disclose the isospin content of the absorptive amplitudes. The results are summarized in Fig. 3 and compared with the updated Paris model calculation [8]. A good understanding of the data is obtained. Two findings are of interest. First there is an enhancement of the P -wave absorptive amplitude just below the threshold. Within the model it corresponds to a quasi-bound 3P_1 state. Second, there is an increase of the S wave absorption down below the threshold. Both these effects are fairly well understood in terms of the model, although the threshold result should be improved.

Nuclear states of antiprotons are expected to be very broad and thus difficult to detect. High angular momentum states are narrow, have been seen indirectly in atoms [19], but otherwise are difficult to produce. An optimal choice seems to be a search for a P state in the reaction ${}^4\text{He} + \bar{p} \rightarrow \bar{p}{}^3\text{H}({}^3P_0) + p$. The indicated 3P_0 state is the lightest nuclear analogue of the ${}^{13}P_0$ resonance in $p\bar{p}$ system. It is likely to be generated by the long tail of π exchange force supplemented by the Coulomb and core interactions. In the suggested process, the final proton energy distribution would consist of a broad structure due to S -wave ${}^3\text{H}-\bar{p}$ interactions. On top of that, Eq. (2) produces a narrow P -wave quasi-free structure given by $|q/(1 + iq^3A_1)|^2$. The averaged ${}^3\text{H}-\bar{p}$ scattering volume from table 1 leads to a few MeV wide peak. In addition, a few MeV below the ${}^3\text{H}-\bar{p}$ threshold one would expect a several MeV wide peak corresponding to the nuclear $\bar{p}{}^3\text{H}({}^3P_0)$ state.

ACKNOWLEDGMENTS

We acknowledge helpful discussions with B. El-Bennich, P. Kienle, W. Kloet, M. Lacombe and J.M. Levy. The LPNHE is an Unité de Recherche des Universités Paris 6 et Paris 7, associée au CNRS. This work was performed in the framework of the IN2P3-Polish Laboratories Convention.

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